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From Aging Farmers to Agri-Tech Innovators: Strategic Pathways for Engaging Millennial Farmers in North Sumatra

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Indonesia's agricultural sector is facing a dual demographic crisis: an aging farming population and a significant disengagement of youth from agricultural livelihoods. This study addresses the urgent need to attract and retain millennial farmers in North Sumatra by applying an integrated Analytical Hierarchy Process (AHP) and SWOT analysis framework. Using a mixed-method approach, data were collected from 120 millennial farmers and key stakeholders across four districts Langkat, Deli Serdang, Serdang Bedagai, and Karo. The study identified six critical factors influencing youth participation: institutional support, education, socioeconomic incentives, land access, technological infrastructure, and motivation. AHP results ranked institutional support as the most influential factor (34.65%), indicating the importance of cooperatives, governance, and extension services. The regional SWOT analysis mapped each district into strategic quadrants (SO, WO, ST, WT), guiding region-specific interventions such as digital incubators, smart horticulture, cooperative reform, and agri-tourism development. Findings underscore the need for spatially sensitive, multi-scalar strategies that combine structural enablers with aspirational rebranding of agriculture. The integration of youth-centered policies, technology access, and institutional support can reposition agriculture as a viable, innovative, and future-oriented career path. This research offers a replicable framework for other regions facing similar challenges and contributes to the broader discourse on sustainable rural transformation aligned with the Sustainable Development Goals (SDGs).

Keywords: Millennial farmers, Agricultural innovation, AHP-SWOT, Youth engagement, Institutional support, Sustainable agriculture, Rural transformation.

INTRODUCTION

Agriculture remains a vital pillar in ensuring food security, regional development, and socio-economic balance in Indonesia, particularly in rural-based provinces such as North Sumatra (Sukiyono, *et al*, 2024; Widyati, *et al*, 2024; Lubis, *et al*, 2022). However, the farming population is rapidly aging, creating structural gaps in labor supply and weakening the continuity of knowledge transfer within farming communities (Song, 2024). This demographic imbalance, if not addressed, may compromise the future of agriculture and threaten regional sustainability goals.

The Indonesian agricultural sector is undergoing a dual crisis: an aging labor force and a lack of youth successors (Rozaki, 2021). Data from Indonesia's Ministry of Agriculture (2022) reveal that nearly 70% of active farmers are over the age of 45, while those under 35 years old represent less than 13% of the workforce (Hasibuan, 2023 and Farahmand, 2025). This trend is mirrored in North Sumatra, where generational handovers in agricultural households are increasingly rare, even in productive zones (Khrisna, 2017).

Table 1. Age Distribution of Farmers in Indonesia and North Sumatra (2022).

Age Group	National (%)	North Sumatra (%)
15-24	02.3%	01.7%
25-34	10.1%	11.2%
35-44	18.4%	20.3%
45-54	32.7%	33.5%
55-64	25.0%	24.1%

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65+	11.5%	9.2%

Source: Indonesia Central Bureau of Statistics (BPS, 2022); North Sumatra Agriculture Agency, 2022.

This table illustrates a clear dominance of older age groups and highlights the urgency of strategic youth integration in agriculture. While national initiatives have emphasized attracting millennials to farming, actual participation remains low (Rachman, 2022). In some districts of North Sumatra, like Langkat and Serdang Bedagai, youth farming cooperatives are underutilized and exhibit high dropout rates, suggesting a mismatch between programs and youth aspirations (Ani, 2024).

A critical barrier to youth engagement in agriculture, particularly among millennials, is the entrenched perception of farming as a low-income and low-prestige profession. Young people increasingly associate agriculture with limited innovation, stagnating opportunities, and restricted pathways for upward mobility (Akrong & Kotu, 2022; Pranandari & Paramita, 2025; Zulu, Djenontin, & Grabowski, 2021). These perceptions are exacerbated by structural constraints, including inadequate access to productive land, digital infrastructure, and start-up capital, which further deter young entrants into the agricultural sector. This challenge is especially acute in peri-urban zones, where rapid urbanization and speculative land markets have accelerated the conversion of agricultural land into commercial and residential developments (Barau, 2017; Dadashpoor & Ahani, 2021; Shah, Ali, & Karim, 2024; Gomes & Hermans, 2018). Such transformations significantly reduce the availability of viable farmland, making it increasingly difficult for new entrants particularly millennials to pursue agriculture as a viable livelihood. Addressing these interconnected challenges requires integrated land-use planning, youth-focused agricultural policy reforms, and inclusive digital and financial infrastructure to restore the attractiveness and feasibility of agriculture for future generations.

Agriculture is increasingly seen as a sector of innovation, driven by digital technologies, agri-preneurship, and green transformation. In Indonesia, the concept of *petani milenial* reflects this policy shift, yet without inclusive and spatially targeted strategies, it risks excluding vulnerable youth. Digital tools improve productivity, income, and rural governance (Mei et al., 2024), and support green agriculture through data-driven resource and market management (Mei et al., 2024). They also reshape knowledge flows and decision-making in farming systems (Schnebelin, Labarthe, & Touzard, 2021), requiring collaboration across sectors to strengthen climate resilience and food security (Harsanto et al., 2025). However, successful adoption depends on innovation capacity, digital infrastructure (Ye, 2025), and addressing low digital literacy among smallholders in developing regions (Jalotjot & Tokuda, 2024).

North Sumatra, with its diverse agro-ecological zones and decentralized governance structure, presents a promising terrain to experiment with youth engagement strategies. The presence of high-value commodities like horticulture in Karo, rice in Serdang Bedagai, and palm oil in Langkat offers varied entry points for youth-centered agricultural innovation (Rifa'I, 2025). Yet, there remains a need to diagnose what strategic interventions would work, where, and why.

To address this need, structured decision-making tools are essential. Methods such as the Analytic Hierarchy Process (AHP) and SWOT analysis offer empirically grounded frameworks to understand both motivation drivers and systemic constraints (Shi, 2025 and Han, 2024). These tools can assist planners in quantifying youth preferences, mapping local institutional readiness, and generating spatially-specific policy responses.

Furthermore, engaging millennial farmers is not solely about tools and incentives it involves transforming the socio-cultural narrative of farming. Evidence suggests that community-based networks, digital platforms, and visibility of role models can create new aspirations around farming as a viable career. Strategic planning must thus address both the material and intangible dimensions of youth engagement.

This study explores strategic pathways to engage millennial farmers through a SWOT-AHP framework applied across four agricultural districts in North Sumatra. The goal is to provide replicable models for regions facing similar demographic and technological transitions in agriculture. The research is grounded in primary data collection and aligned with broader sustainability goals (Liu, 2023).

What are the key socio-economic and technological factors influencing youth engagement in agriculture in North Sumatra?

1. How can an integrated AHP-SWOT framework inform territorial strategies to attract and retain millennial farmers?
2. What policy and institutional mechanisms are required to sustain youth-led innovation in the regional agricultural sector?

MATERIALS AND METHODS

***Research Design*:** This study adopts a convergent mixed-methods approach that integrates quantitative decision-making models with qualitative participatory techniques to formulate spatially grounded strategies for youth engagement in agriculture. The core methodological framework synthesizes the Analytic Hierarchy Process (AHP) and SWOT analysis, enabling multi-criteria prioritization and strategic mapping. These tools were applied across four purposively selected agricultural districts in North Sumatra—Langkat, Deli Serdang, Serdang Bedagai, and Karo—each representing distinct agro-ecological zones and commodity orientations.

***Sampling and Data Collection*:** Primary data collection was conducted in two sequential phases:

Phase 1 involved structured surveys and focus group discussions (FGDs) with 120 respondents, including millennial farmers (aged 19-39), agricultural extension officers, and district-level officials. Participants were selected using stratified purposive sampling to ensure representation across demographic categories and geographic zones.

Phase 2 collected expert judgments from 12 key informants, including agricultural planners and community leaders, to inform the AHP's pairwise comparison matrix.

All participants were screened for relevant experience or engagement in the agricultural sector. Ethical protocols regarding informed consent and data confidentiality were strictly observed.

***Analytical Hierarchy Process* (AHP):** The AHP is used to prioritize decision criteria affecting youth participation in agriculture (Shen, 2024). It involves three steps: (1) developing a hierarchy of decision criteria, (2) pairwise comparisons, and (3) calculating priority weights.

Step 1: Construct Hierarchy

The criteria used include:

- C_1: Motivation & Interest
- C_2: Socioeconomic Support
- C_3: Land & Capital Access
- C_4: Training & Education
- C_5: Technological Infrastructure

Step 2: Pairwise Comparison

Each element is compared using Saaty's scale (1-9). The matrix A=[a_{ij}] constructed where:

$$a = \frac{wi}{wj}, \text{ and } a = \frac{1}{a_{ij}}$$

Step 3: Normalization & Priority Vector

Each element of matrix A is normalized as:

$$a_{ij}^{norm} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}}$$

The priority vector W is then computed:

$$W_j = \frac{\sum_{i=1}^{n} a_{ij}^{norm}}{n}$$

Step 4: Consistency Check

The Consistency Index (CI) is calculated as:

$$CL = \frac{\lambda_{max} - n}{n - 1}$$

Where λ_{max} is the principal eigenvalue:

$$\lambda_{max} = \sum_{i=1}^{n} (A.W_i) \div W_i$$

The Consistency Ratio (CR) is:

$$CR = \frac{CI}{RI}$$

Where RI is the Random Index from Saaty's scale. If CR<0., consistency is acceptable.

***SWOT Analysis*:** SWOT analysis identifies internal (strengths/weaknesses) and external (opportunities/threats) factors based on field and policy review data. SWOT factors are then weighted using AHP-derived weights to produce a strategic quadrant.

Let Si,Wi,Oi,Ti be the respective factors, and w_i their AHP weights. Total scores for each quadrant are computed as:

$$SO = \sum(S_i . O_i),\ WO = \sum(W_i . O_i)$$
$$SO = \sum(S_i . T_i), WT = \sum(W_i . T_i)$$

The quadrant with the highest combined score determines the recommended strategy.

***Analytical Integration Procedure*:** To enable a spatially explicit policy framework, the outputs from the AHP and SWOT analyses were synthesized using a multi-criteria integration matrix. This step involved the development of a comparative scoring table combining:

1. AHP Priority Scores: Reflecting the relative importance of youth engagement drivers per region.
2. SWOT Strategic Quadrants: As determined by weighted scoring of internal and external factors.
3. GPI (Geographic Potential Index): A spatial development score calculated based on district-level agricultural infrastructure, youth demographics, and land-use characteristics. The GPI score provided a spatial lens to prioritize intervention efforts.

This integration served purely as a methodological structuring tool. The detailed interpretations, strategic implications, and region-specific planning recommendations are presented in the subsequent Results and Discussion section.

RESULT AND DISCUSSION

***AHP Analysis*: *Prioritization of Strategic Drivers*:** The Analytic Hierarchy Process (AHP) was applied to evaluate six primary factors influencing youth participation in agriculture. Each factor was assessed through a structured pairwise comparison approach, involving expert judgment and weighted aggregation using Super Decisions software.

As shown in Figure 1, the most influential factor is institutional support (*kelembagaan*) with a priority weight of 0.34654, followed by education (0.16795) and socioeconomic incentives (0.15736). Motivation scored the lowest, indicating that without enabling structures, intrinsic interest alone is insufficient to attract young people to farming.

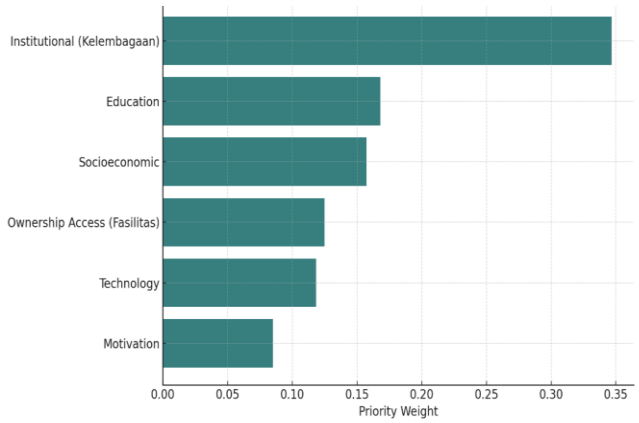

Figure 1. AHP Weights for Affecting Millennial Farmers' Interests.

The regional coordinates are plotted and categorized into the classic SWOT quadrants: SO (Aggressive), WO (Diversification), ST (Competitive), WT (Defensive). These are then aligned with the AHP-derived factor weights to create region-specific strategies.

Table 3. AHP Local Priorities for Youth Engagement Factors.

Criteria	Weight
Institutional (Kelembagaan)	0.34654
Education	0.16795
Socioeconomic	0.15736
Ownership Access (Fasilitas)	0.12499
Technology	0.11828
Motivation	0.08488

Institutional support (34.65%) emerged as the dominant enabler, signifying that access to functioning cooperatives, active extension agents, and supportive governance are essential for youth involvement. Conversely, motivation (8.5%), although critical, is insufficient on its own without systemic reinforcement. These weights were used to enrich SWOT quadrant scoring per region.

***Regional SWOT Mapping and Strategic Positioning*:** Each region was assessed on four factors: Strengths (S), Weaknesses (W), Opportunities (O), and Threats (T). Using the formula:

X=Strengths − Weakness, Y = Opportunities - Threats

we computed quadrant coordinates and interpreted results region-by-region.

Langkat: WO Strategy (Quadrant II - Diversification)

- SWOT Scores: $S = 1.4\ W = 2.2, O = 2.5, T = 1.4$
- Position: $X = -0.8, Y = +1.1$ Quadrant II (WO)

Langkat suffers from internal deficiencies—limited youth-centered institutions and low-quality extension outreach—but benefits from strong commodity networks (palm oil, rice) and programmatic support from provincial agencies. The high AHP weight on institutional factors (0.34654) makes this region suitable for leveraging external policy programs to overcome internal weaknesses. Recommended strategies include establishing youth-based agri-cooperatives and expanding training programs via local agriculture polytechnics.

Deli Serdang: SO Strategy - Aggressive Youth Investment

SWOT Scores: $S = 1.6\ W = 2.0, O = 2.3, T = 1.6$

- Position: $X = -0.4, Y = +0.7$ Quadrant I (SO)

Deli Serdang lies near the economic belt of North Sumatra and is adjacent to major urban centers. This provides an opportunity to scale digital agriculture, especially e-commerce integration for young farmers. The combined strength in education (AHP: 0.16795) and infrastructure enables a proactive agri-tech incubation strategy. Youth-led cooperatives in peri-urban zones can act as innovation labs to demonstrate sustainable farming as a profitable business.

Serdang Bedagai: WT Strategy - Stabilization and Support

- SWOT Scores: $S = 1.3\ W = 2.5, O = 2.1, T = 1.7$
- Position: $X = -1.2, Y = +0.7$ Quadrant I (SO)

Karo: ST Strategy (Quadrant IV - Competitive)

- Scores:
  S=1.7S = 1.7S=1.7, W=1.9W = 1.9W=1.9 → X=−0.2X = -0.2X=−0.2
  O=2.6O = 2.6O=2.6, T=1.5T = 1.5T=1.5 → Y=+1.1Y = +1.1Y=+1.1
- Position:
  Near zero on X, but dominant external opportunities push it to Quadrant IV (ST).
- Interpretation:
  Known for its horticulture and highland produce, Karo has strong cultural cohesion but youth are migrating due to climate risks. Technology (AHP: 0.11828) and education remain top levers.
- Strategy:
  Develop smart horticulture programs, and enable youth in agri-tourism and supply chain leadership.

Table 5. SWOT-AHP Strategic Quadrant Summary for Millennial Farmer Development.

Region	X	Y	Quadrant	Strategy Focus
Langkat	-0.8	+1.1	II (WO)	Institutional building, agri-training
Deli Serdang	-0.4	+0.7	I (SO)	Digital incubators, tech partnerships
Serdang Bedagai	-1.2	+0.4	III (WT)	Subsidy + cooperative restructuring
Karo	-0.2	+1.1	IV (ST)	Smart horticulture, agro-tourism

Geographic Potential Index (GPI) Assessment

To complement the SWOT-AHP strategic quadrant mapping, a Geographic Potential Index (GPI) was constructed to assess

the spatial readiness of districts in North Sumatra for engaging millennial farmers. The GPI provides a composite measure of a region's developmental potential by combining AHP-derived factor weights with internal performance data drawn from the Internal Factor Evaluation (IFAS) matrix.

The GPI was calculated using a weighted sum model:

$$GPI = \sum i = (IFAS\ Score_i \times AHP\ Weight_i)$$

This formulation enables the translation of internal strengths (e.g., education, motivation) into a quantifiable index that reflects how conducive a region is to supporting youth-led agricultural development.

Table 6. GPI Components and Weighted Scores (Pilot Assessment).

Aspect	IFAS Score	AHP Weight	Weighted Contribution
Motivation	1.46	0.08488	0.124
Education	2.37	0.16795	0.398
Ownership Facilities	Not yet available	0.12499	—
Technology	Not yet available	0.11828	—
Socio-economic	Not yet available	0.15736	—
Institutional Support	Not yet available	0.34654	—
Total GPI (Partial)		—	0.522

The partial GPI score of 0.522 suggests a moderate level of spatial and institutional readiness in regions where motivation and education have been quantitatively assessed. The high contribution from education (0.398) reflects the role of formal and informal learning pathways as a significant enabler of millennial farmer participation.

However, the absence of data for critical dimensions such as institutional support, socioeconomic

infrastructure, and technological readiness limits the full interpretive capacity of this initial index. Given that institutional support holds the highest AHP weight (0.34654), incorporating this aspect is essential for refining the GPI and accurately ranking regional potential.

The GPI framework serves as a vital intermediary between theoretical strategy and practical implementation. While SWOT-AHP analysis identifies "what" strategies are suitable, the GPI helps determine "where" to prioritize policy interventions. For instance:

- Regions with a high GPI and favorable SWOT quadrant (e.g., SO or ST) are ideal candidates for piloting youth-led agri-innovation programs.Regions with a low GPI, even if strategically favorable, may require foundational investments in education, institutional reform, and infrastructure.

In summary, the GPI reinforces the need for evidence-based spatial planning in rural development policy. Future iterations of the index, once additional IFAS and EFAS data are integrated, will allow for more precise regional ranking and resource targeting.

CONCLUSION AND POLICY RECOMMENDATIONS

***Conclusion*:** This study has demonstrated the urgency and potential for engaging millennial farmers in North Sumatra through a structured and context-sensitive strategic framework. The aging agricultural workforce, declining rural participation among youth, and structural barriers such as poor institutional support and limited land access pose significant threats to sustainable agricultural development in Indonesia.

By integrating the Analytic Hierarchy Process (AHP) and SWOT analysis, we have identified critical enablers of youth participation—most notably, institutional infrastructure, education, and socioeconomic incentives. The regional analysis across Langkat, Deli Serdang, Serdang Bedagai, and Karo highlights that no single strategy fits all contexts. Instead, youth engagement must be regionally tailored, combining technological adoption, cooperative reform, agri-tourism, and digital innovation.

The results reinforce that motivation among youth is insufficient in isolation. Tangible enablers—like functioning agricultural cooperatives, supportive governance, modern agri-tech tools, and land accessibility—are indispensable. Importantly, spatial diversity in agro-ecological and socio-economic conditions necessitates multi-scalar policies, addressing both systemic constraints and individual aspirations.

Engaging millennials in agriculture is not merely a demographic imperative—it is a strategic investment in national food security, innovation ecosystems, and rural transformation aligned with SDGs on decent work (SDG 8), innovation (SDG 9), and food security (SDG 2).

Policy Recommendations

Table 7. Policy Recommendations

Region / Focus Area	Strategic Type	Key Policy Interventions
Langkat	WO - Diversification	- Establish youth-oriented agri-cooperatives - Expand polytechnic-led agricultural training - Utilize provincial support to strengthen institutions
Deli Serdang	SO - Aggressive Growth	- Launch digital agri-tech incubators in peri-urban zones - Provide micro-grants for start-up agri-enterprises - Foster public-private R&D partnerships with universities

Serdang Bedagai	WT - Stabilization	- Introduce land access schemes for youth (credit, lease, inheritance incentives) - Restructure youth cooperatives for better governance - Offer targeted subsidies (tools, internet, training)
Karo	ST - Competitive Edge	- Promote climate-resilient smart farming technologies - Support youth-led agri-tourism and branding of local produce - Provide training in supply chain and post-harvest leadership

These region-specific recommendations highlight the need for localized, evidence-based strategies to engage millennial farmers. By integrating SWOT-AHP analysis with GPI scoring, the study offers a replicable model to guide strategic agricultural planning and youth empowerment aligned with national sustainability goals.

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Conflict of interest: The authors declare that there is no conflict of interest regarding the publication of this article.

Ethical statement: This study followed ethical research standards and respected the confidentiality and voluntary participation of all respondents. No personal identifying information was collected.

***Availability of data*:** The datasets generated and analyzed during this study are available from the corresponding author upon reasonable request.

***Consent to participate*:** All participants provided voluntary consent to take part in the surveys, interviews, and focus group discussions included in this research.

***Informed consent*:** Informed consent was obtained from all individual participants involved in the study. No minors or vulnerable groups were included without proper consent.

***Consent for publication*:** All authors have reviewed and approved the final version of this manuscript and consent to its publication in the Journal of Global Innovations in Agricultural Sciences (JGIAS).

***SDGs addressed*:** No poverty; Zero Hunger; Quality Eduation.

Policy referred: *Ministry of Agriculture Strategic Plan (Renstra Kementerian Pertanian);* Agrarian Reform and Social Forestry Policy.

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REFERENCES

Akrong, R., & Kotu, B. H. (2022). Economic analysis of youth participation in agripreneurship in Benin. *Heliyon, 8*(1), e08738. https://doi.org/10.1016/j.heliyon.2022.e08738

Ani, S. W., Darwanto, D. H., Waluyati, L. R., & Masyhuri. (2024). Regeneration of rural rice farmers in Central Java Province. *Environmental Challenges, 16*, 100971. https://doi.org/10.1016/j.envc.2024.100971

Barau, A. S. (2017). Tension in the periphery: An analysis of spatial, public and corporate views on landscape change in Iskandar Malaysia. *Landscape and Urban Planning, 165*, 256-266. https://doi.org/10.1016/j.landurbplan.2016.04.007

Dadashpoor, H., & Ahani, S. (2021). Explaining objective forces, driving forces, and causal mechanisms affecting the formation and expansion of the peri-urban areas: A critical realism approach. *Land Use Policy, 102*, 105232. https://doi.org/10.1016/j.landusepol.2020.105232

Farahmand, H., Tajrishy, M., Isaai, M. T., Ghoreishi, M., & Mohammadi, M. (2025). Introducing the REPAIR framework for sustainable environmental restoration: Lessons from Lake Urmia, Iran. *Journal of Arid Environments, 229*, 105369. https://doi.org/10.1016/j.jaridenv.2025.105369

Gomes, S. L., & Hermans, L. M. (2018). Institutional function and urbanization in Bangladesh: How peri-urban communities respond to changing environments. *Land Use Policy, 79*, 932-941. https://doi.org/10.1016/j.landusepol.2017.09.041

Han, Q., Guo, Z., Kumar, R., & Kumar, A. (2024). An empirical approach for enhancing farmers' concentrated residence strategies: A case study in Jiangsu Province, China. *Ecological Indicators, 158*, 111361. https://doi.org/10.1016/j.ecolind.2023.111361

Harsanto, B., Kasumaningrum, Y., Arviansyah, M. R., Siregar, A. Y. M., Purnomo, D., Freddy, Iskandar, Y., Utama, I. D., & Sari, D. I. (2025). Leveraging disruptive technologies for food security: A systematic review on agricultural supply chain resilience to climate change. *Current Research in Food Science, 10*,101079. https://doi.org/10.1016/j.crfs.2025.101079

Hasibuan, A. M., Wulandari, S., Ardana, I. K., Saefudin, & Wahyudi, A. (2023). Understanding climate adaptation practices among small-scale sugarcane farmers in Indonesia: The role of climate risk behaviors, farmers' support systems, and crop-cattle integration. *Resources, Environment and Sustainability, 13*, 100129. https://doi.org/10.1016/j.resenv.2023.100129

Jalotjot, H. C., & Tokuda, H. (2024). Exploring smallholder farmers' open innovation capability: A structural equation modeling approach. *Journal of Open Innovation: Technology, Market, and Complexity, 10*(2), 100305. https://doi.org/10.1016/j.joitmc.2024.100305

Khrisna, V. V., Kubitza, C., Pascual, U., & Qaim, M. (2017). Land markets, property rights, and deforestation: Insights from Indonesia. *World Development, 99*, 335-349. https://doi.org/10.1016/j.worlddev.2017.05.018

Liu, S. (2023). *Towards a sustainable agriculture: Achievements and challenges of Sustainable Development Goal Indicator 2.4.1*. *Global Food Security*, 37, 100694. https://doi.org/10.1016/j.gfs.2023.100694

Lubis, (2022). Production and demand forecasting analysis of rice in North Sumatra in 2030. IOP Conference Series: Earth and Environmental Science ISSN: 17551307 Volume: 977 Issue: 1 Conference Paper Open Access 2022 EID: 2-s2.0-85135192528 https://doi.org/10.1088/1755-1315/977/1/012060

Mei, L., Zheng, Y., Tian, M., & Wu, Y. (2024). Driven by the policy or bent by the market? Cracking the digital transformation code of farmer cooperatives. *Technological Forecasting and Social Change, 208*, 123659. https://doi.org/10.1016/j.techfore.2024.123659

Pranandari, A., & Paramita, W. (2025). Signaling competence of agricultural businesses through social media presence to attract Gen Z. *Digital Business, 5*(1), 100117. https://doi.org/10.1016/j.digbus.2025.100117

Rachman, B., Ariningsih, E., Sudaryanto, T., Ariani, M., Septanti, K. S., Adawiyah, C. R., et al. (2022). Sustainability status, sensitive and key factors for increasing rice production: A case study in West Java, Indonesia. *PLOS ONE, 17*(12), e0274689. https://doi.org/10.1371/journal.pone.0274689

Rifa'i, A. (2025). Economy-wide impacts of palm oil downstream in North Sumatra: A CGE approach. *World Development Perspectives, 39*, 100706. https://doi.org/10.1016/j.wdp.2025.100706

Rozaki, Z. (2021). Food security challenges and opportunities in Indonesia post COVID-19. In *Advances in Food Security and Sustainability* (Vol. 6, pp. 119-168). Elsevier. https://doi.org/10.1016/bs.af2s.2021.07.002

Schnebelin, É., Labarthe, P., & Touzard, J.-M. (2021). How digitalisation interacts with ecologisation? Perspectives from actors of the French Agricultural Innovation System. *Journal of Rural Studies, 86*,599-610. https://doi.org/10.1016/j.jrurstud.2021.07.023

Shah, A., Ali, K., & Karim, R. (2024). Assessment of peri-urban land dynamics using GIS remote sensing: A case study of Hunza City in Northern Pakistan. In *Modern Cartography Series* (Vol. 11, Chapter 13, pp. 315-328). Elsevier. https://doi.org/10.1016/B978-0-443-15832-2.00013-7

Shen, P. (2024). Assessment of child-friendly spatial environment in urban communities based on fuzzy Analytic Hierarchy Process. *Journal of Engineering Research*. Advance online publication. https://doi.org/10.1016/j.jer.2024.05.020

Shi, C., Li, J., Zhan, H., Feng, Y., Wang, J., Xiao, Z., & Shu, Y. (2025). Evaluating the impact of Bt rice straw return on *Eisenia fetida*: AHP analysis, biomarkers, and Bt protein fate. *Ecotoxicology and Environmental Safety, 290*, 117592. https://doi.org/10.1016/j.ecoenv.2024.117592

Song, H., Jiang, C., & Sun, Z. (2024). Unveiling the nexus between rural population aging, technical efficiency, and carbon emissions in Chinese agriculture. *PLOS ONE, 19*(6), e0300124. https://doi.org/10.1371/journal.pone.0300124

Sukiyono, K., Romdhon, M. M., Mulyasari, G., Yuliarso, M. Z., Nabiu, M., Trisusilo, A., Reflis, Napitupulu, D. M. T., Nugroho, Y., Puspitasari, M. S., Sugiardi, S., Arifudin, & Masliani. (2024). Smallholder palm oil and sustainable development goals (SDGs) achievement: An empirical analysis. *Sustainable Futures, 8*,100233. https://doi.org/10.1016/j.sftr.2024.100233

Widyati, E., Irianto, R. S. B., Dewi, T., Maftu'ah, E., Hartatik, S. E., & Parray, J. A. (2024). Emerging strategies for engineering microbial communities to augment bioremediation in Indonesia. In *Microbiome-Assisted Bioremediation: Rehabilitating Agricultural Soils* (Chapter 19, pp. 401-427). In *Microbiome Research in Plants and Soil*. Elsevier. https://doi.org/10.1016/B978-0-443-21911-5.00009-X

Ye, L. (2025). Digital economy and high-quality agricultural development. *International Review of Economics & Finance, 99*, 104028. https://doi.org/10.1016/j.iref.2025.104028

Zulu, L. C., Djenontin, I. N. S., & Grabowski, P. (2021). From diagnosis to action: Understanding youth strengths and hurdles and using decision-making tools to foster youth-inclusive sustainable agriculture intensification. *Journal of Rural Studies, 82*, 196-209. https://doi.org/10.1016/j.jrurstud.2021.01.023